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Branching Fraction for the Doubly-Cabibbo-Suppressed Decay $D^+ \to K^+\pi^0$

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Abstract

We present a measurement of the branching fraction for the doubly-Cabibbo-suppressed decay $D^+ \to K^+\pi^0$, using 281 pb^{-1} of data accumulated with the CLEO-c detector on the $\psi(3770)$ resonance. We find $\mathcal{B}\left(D^+ \to K^+\pi^0\right) = (2.28 \pm 0.36 \pm 0.15 \pm 0.08) \times 10^{-4}$, where the first uncertainty is statistical, the second is systematic, and the last error is due to the uncertainty in the reference mode branching fraction.

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The Cabibbo-favored hadronic decays of the c quark proceed through $c \to sW_V^+$, $W_V^+ \to u\overline{d}$ (W_V^+ a virtual W^+ boson). The doubly-Cabibbo-suppressed decays proceed through $c \to dW_V^+$, $W_V^+ \to u\overline{s}$, and are expected to be suppressed by a factor $|(V_{cd}V_{us})/(V_{cs}V_{ud})|^2 \approx 2.5 \times 10^{-3}$. The doubly-Cabibbo-suppressed decay $D^0 \to K^+\pi^-$ was first observed in 1994 [1], and its branching fraction is now known to good precision ($\pm 2.8\%$, relative [2]). Its ratio to the Cabibbo-favored decay $D^0 \to K^-\pi^+$ is measured to be $(3.76 \pm 0.09)\times 10^{-3}$ [2], in qualitative agreement with the simple expectations. Very recently BaBar has observed [3] a second $D \to K\pi$ doubly-Cabibbo-suppressed decay $D^+ \to K^+\pi^0$ (charge-conjugate mode $D^- \to K^-\pi^0$ implied also, throughout). Here we report confirmation of BaBar's result, with slightly better accuracy. These measurements can provide insight into the decay mechanisms for $D \to K\pi$: the validity of SU(3), and the roles of the annihilation, exchange, and color-suppressed spectator diagrams relative to the color-favored spectator diagram [4, 5]. A more extensive picture will be provided by the measurement of the remaining two $D \to K\pi$ doubly-Cabibbo-suppressed decays, $D^+ \to K^0\pi^+$ and $D^0 \to K^0\pi^0$.

For this measurement, we have used a 281 pb^{-1} sample of e^+e^- colliding beam events, collected at a center-of-mass energy of 3770 MeV. The events were produced with the CESR-c storage ring and detected with the CLEO-c detector. The data sample contains about 0.8×10^6 D^+D^- events (our target sample), one million $D^0\overline{D}^0$ events, five million $e^+e^- \to u\overline{u}$, $d\overline{d}$, or $s\overline{s}$ continuum events, one million $e^+e^- \to \tau^+\tau^-$ events, and one million $e^+e^- \to \gamma\psi'$ radiative return events (sources of background), as well as Bhabha events, μ-pair events, and $\gamma\gamma$ events (useful for luminosity determination and resolution studies).

The CLEO-c detector is a general purpose solenoidal detector which includes a tracking system for measuring momenta and specific ionization (dE/dx) of charged particles, a Ring Imaging Cherenkov detector (RICH) to aid in particle identification, and a CsI calorimeter for detection of electromagnetic showers. The CLEO-c detector is described in detail elsewhere [6, 7, 8].

The $\psi(3770)$ resonance is below the kinematic threshold for $D\overline{D}\pi$ production, and so the events of interest, $e^+e^- \to \psi(3770) \to D\overline{D}$, have D mesons with energy equal to the beam energy. Having picked the particles being considered to make up a D meson, following Mark III [9] we define the two variables:

$$\Delta E \equiv \sum_i E_i - E_{\rm beam}, \tag{1}$$

and

$$M_{\rm bc} \equiv \sqrt{E_{\rm beam}^2 - |\sum_i \vec{P}_i|^2}, \tag{2}$$

where E_i, $\vec{P}_i$ are the energy and momentum of each D decay product. For a correct combination of particles, ΔE will be consistent with zero, and the beam-constrained mass $M_{\rm bc}$ will be consistent with the D mass.

In addition to $D^+ \to K^+\pi^0$, we have studied the singly-Cabibbo-suppressed decay $D^+ \to \pi^+\pi^0$, as a higher-rate decay possessing kinematics similar to $D^+ \to K^+\pi^0$, and the Cabibbo-favored decay $D^+ \to K^-\pi^+\pi^+$, as a high-rate, low-background mode used for normalization. We distinguish between $K^\pm$ and $\pi^\pm$ using information from the RICH and dE/dx information from the central drift chamber. We identify π^0's via $\pi^0 \to \gamma\gamma$, detecting the photons in the CsI calorimeter. We require that the calorimeter clusters have a measured

energy above 30 MeV, have a lateral distribution consistent with that from photons, and are not matched to any charged track. We require that the $\gamma\gamma$ invariant mass be within 3 standard deviations of the π^0 mass. The π^0 mass resolution is 5.4 MeV (Gaussian width σ) for both $D^+ \to K^+\pi^0$ and $D^+ \to \pi^+\pi^0$. The ΔE resolution is 14 MeV for $D^+ \to K^+\pi^0$, 15 MeV for $D^+ \to \pi^+\pi^0$, and 5.6 MeV for $D^+ \to K^-\pi^+\pi^+$. The $M_{\rm bc}$ resolution is 1.90 MeV for $D^+ \to K^+\pi^0$, 1.96 MeV for $D^+ \to \pi^+\pi^0$, and 1.35 MeV for $D^+ \to K^-\pi^+\pi^+$.

We select candidate combinations that have ΔE between -40 MeV and $+35$ MeV for $K^+\pi^0$ and $\pi^+\pi^0$, and between -20 MeV and $+20$ MeV for $K^-\pi^+\pi^+$. These requirements correspond to roughly 3 standard deviations. The asymmetric cut for $K^+\pi^0$ and $\pi^+\pi^0$ is due to a low-side tail on π^0 energies, and the wider window is due to poorer energy resolution. To study background, we select combinations with ΔE between -100 and -50 MeV, and between $+45$ and $+100$ MeV ($+50$ and $+100$ MeV for $K^-\pi^+\pi^+$). When an event contains more than one $K^+\pi^0$ combination that passes our ΔE requirement (a 1.4% occurrence), we choose the combination with ΔE value closest to zero. Multiple candidates per event for $\pi^+\pi^0$ and for $K^-\pi^+\pi^+$ are comparable in frequency, and are removed by the same procedure. Thus, we allow only one candidate per event per decay mode per D charge. For those multiple candidate events that contain a real $D^+ \to K^+\pi^0$ decay, Monte Carlo studies indicate that our algorithm for picking the "best candidate" gets the right one 2/3 of the time. Because the algorithm uses ΔE only, and our procedure for extracting yield uses a fit to $M_{\rm bc}$, the algorithm introduces no bias.

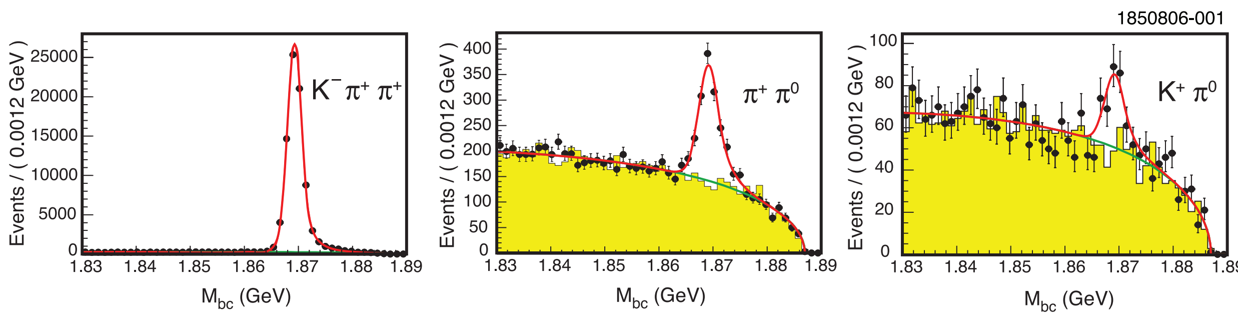

FIG. 1: $M_{\rm bc}$ distributions of $D^+ \to K^-\pi^+\pi^+$, $D^+ \to \pi^+\pi^0$ and $D^+ \to K^+\pi^0$. The points are obtained by selecting the ΔE signal region, the shaded histogram is from the ΔE sidebands, and the lines are the fit described in the text.

The $M_{\rm bc}$ distributions for candidate combinations are shown in Fig. 1. The normalization mode $D^+ \to K^-\pi^+\pi^+$ is essentially background-free. The $D^+ \to \pi^+\pi^0$ mode background is well described by the distribution obtained from the ΔE sideband, as is that for the $D^+ \to K^+\pi^0$ mode. There is a clear peak in $D^+ \to K^+\pi^0$.

Our Monte Carlo studies indicate that 80% of the background to $D^+ \to K^+\pi^0$ comes from continuum events, 11% from $D\overline{D}$ events, 8% from radiative return events, and 1% from τ-pair events. The ΔE requirement cleanly separates $D^+ \to K^+\pi^0$ and $D^+ \to \pi^+\pi^0$ decays, so there is no cross-talk between these modes. There is no evidence for peaking backgrounds.

We perform an unbinned maximum likelihood fit to extract signal yields from the $M_{\rm bc}$ distributions. For the signal, we use a Crystal Ball line shape [10], which is a Gaussian with a high-side tail. As Monte Carlo studies show that $D^+ \to K^+\pi^0$ and $D^+ \to \pi^+\pi^0$ have the same signal shapes, we have determined the line shape parameters (Gaussian peak

location, Gaussian width, point at which high-side tail begins) from the $D^+ \to \pi^+\pi^0$ $M_{\rm bc}$ distribution, and used them in the fit to the $D^+ \to K^+\pi^0$ $M_{\rm bc}$ distribution. We have varied the shape of the high-side tail as part of the systematic error study. For the background, we use an ARGUS function [11], with shape parameter determined from the ΔE sideband $M_{\rm bc}$ distribution, high-end cutoff given by $E_{\rm beam}$, and normalization determined from the fit to the ΔE signal region. Monte Carlo studies demonstrate that the shape parameter determined from the ΔE sideband correctly describes the shape of the background in the ΔE signal region. We have also performed a fit with the ARGUS shape parameter free in the fit, and obtained essentially the same result.

TABLE I: The efficiencies (from Monte Carlo, but corrected for π^0-finding (see below)), fit yields from data, and branching fractions from data. Only statistical uncertainties are included.

Mode	ϵ (%)	Signal yield	$\mathcal{B}$ (%)
$D^+ \to K^-\pi^+\pi^+$	52.16 ± 0.16	79612 ± 291	9.51 (Input)
$D^+ \to \pi^+\pi^0$	47.65 ± 0.15	964 ± 54	0.1326 ± 0.0075
$D^+ \to K^+\pi^0$	42.30 ± 0.14	148 ± 23	0.0228 ± 0.0036

Results of the fits are shown in Table I. Also given in Table I is the detection efficiency for each mode, and the branching fractions obtained for $D^+ \to \pi^+\pi^0$ and $D^+ \to K^+\pi^0$. Those branching fractions are obtained by measuring the respective efficiency-corrected yields relative to that for $D^+ \to K^-\pi^+\pi^+$, taking that branching fraction as $(9.51 \pm 0.34)\%$, which is taken from the 2006 Particle Data Group (PDG) value [2]. The branching fraction for $D^+ \to \pi^+\pi^0$ is in good agreement with our previously-published branching fraction using the same data set, $(0.125 \pm 0.006 \pm 0.007 \pm 0.004)\%$ [12]. We emphasize that these results are *not* independent, and the value in this paper should *not* be used in place of the previous result.

We have considered many sources of systematic error to the $D^+ \to K^+\pi^0$ branching fraction, including: signal Monte Carlo statistics, track-finding efficiency, π^0-finding efficiency, particle identification, the ΔE requirement, final state radiation, and the uncertainty from our fitting procedure (background shape, signal shape). The only ones greater than 1/10 of the statistical error are π^0-finding efficiency, background shape, and signal shape.

The Monte Carlo simulation of the calorimeter response to photons is imperfect, particularly in those angular regions where there is considerable material between the interaction point and the calorimeter. The Monte Carlo simulation overestimates the efficiency for detecting π^0's. Various data-Monte Carlo comparisons suggest a correction factor of (0.95 ± 0.04), which we apply.

The background shape is determined by a fit to the ΔE sideband data. The error on the shape parameter thus obtained translates into a $\pm 4.4\%$ relative error in the $D^+ \to K^+\pi^0$ branching fraction. The signal shape is determined by a fit to the $D^+ \to \pi^+\pi^0$ signal. Uncertainty comes from the determination of Gaussian width (σ), and the point at which non-Gaussian tail sets in (α). We have obtained the error ellipse in the determination of these two parameters, and noted the variation in fitted $D^+ \to K^+\pi^0$ yield as one travels around this error ellipse. In this way, we obtain a relative systematic error of $\pm 2.6\%$. Note that both the background shape uncertainty and signal shape uncertainty are really statistical errors, hence will decrease as additional data are taken.

We have also considered systematic errors to our normalizing mode, $D^+ \to K^-\pi^+\pi^+$, *i.e.*, to the yield and to the efficiency. Because this mode is essentially background-free, background shape and signal shape contribute negligible errors. Kaon particle identification tends to cancel in the ratio to $D^+ \to K^+\pi^0$. Pion particle identification efficiency is well-modeled by Monte Carlo simulation. Track-finding efficiency – 3 tracks in normalizing mode *vs.* 1 track in signal mode, with 0.7% uncertainty per track – is the largest error, and is less than 1/10 the overall statistical error (1.4% *vs.* 16%).

Our final result is

$$\mathcal{B}\left(D^+ \to K^+\pi^0\right) = (2.28 \pm 0.36 \pm 0.15 \pm 0.08) \times 10^{-4},$$

where the first error is statistical, the second error is systematic, and the third error is from the uncertainty in the $D^+ \to K^-\pi^+\pi^+$ branching fraction, (9.51 ± 0.34)% [2], used as the normalizing mode.

Our result is in good agreement with the only other measurement of this branching fraction, BaBar's recent $\mathcal{B}(D^+ \to K^+\pi^0) = (2.52 \pm 0.47 \pm 0.25 \pm 0.08) \times 10^{-4}$ [3]. It can be converted to a width, using the PDG value for the D^+ lifetime ($(1040 \pm 7) \times 10^{-15}$ s) [2], and compared with the width for doubly-Cabibbo-suppressed D^0 decay $D^0 \to K^+\pi^-$, using the PDG values for the $D^0 \to K^+\pi^-$ branching fraction ($(1.43 \pm 0.04) \times 10^{-4}$) [2] and D^0 lifetime ($(410.1 \pm 1.5) \times 10^{-15}$ s) [2]. In this way we obtain

$$\frac{\Gamma(D^+ \to K^+\pi^0)}{\Gamma(D^0 \to K^+\pi^-)} = \frac{\mathcal{B}(D^+ \to K^+\pi^0) \times \tau_{D^0}}{\mathcal{B}(D^0 \to K^+\pi^-) \times \tau_{D^+}} = 0.63 \pm 0.11 \ .$$

The spectator model diagram, expected to be the dominant contribution, predicts 1/2 for the ratio. Annihilation and exchange diagrams, which contribute differently to the two decays, can shift the ratio away from 1/2. Our result, and the BaBar result [3], suggest that such a shift is small.

In summary, we have measured the branching fraction for $D^+ \to K^+\pi^0$ to be $(2.28 \pm 0.36 \pm 0.15 \pm 0.08) \times 10^{-4}$, in agreement with the only other measurement of that branching fraction, and of comparable accuracy.

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